The Unusual Spectral Energy Distribution of a Galaxy Previously Reported to be at Redshift 6.68

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Observations of distant galaxies are important both for understanding how galaxies form and for probing the physical conditions of the universe at the earliest epochs. It is, however, extremely difficult to identify galaxies at redshift $z > 5$, because these galaxies are faint and exhibit few spectral features. In a previous work, we presented observations that supported the identification of a galaxy at redshift $z = 6.68$ in a deep STIS field[1]. Here we present new ground-based photometry of the galaxy. We find that the galaxy exhibits moderate detections of flux in the optical B and V images that are inconsistent with the expected absence of flux at wavelength shortward of the redshifted Lyman-α emission line of a galaxy at redshift $z > 5$. In addition, the new broad-band imaging data not only show flux measurements of this galaxy that are incompatible with the previous STIS measurement, but also suggest a peculiar spectral energy distribution that cannot be fit with any galaxy spectral template at any redshift. We therefore conclude that the redshift identification of this galaxy remains undetermined.

The galaxy (designated galaxy A by Chen, Lanzetta, & Pascarelle[1]) was previously identified in deep observations obtained by the Hubble Space Telescope using the Space Telescope Imaging Spectrograph (STIS) in 1997 December. It has a STIS clear magnitude of $AB(\text{clear}) = 27.67 \pm 0.09$. The spectrum of galaxy A was extracted using a new spectrum extraction technique that employed optimal weights to spatially deblend and spectrally deconvolve the slitless spectra. The spectrum was characterized by a discontinuity at wavelength $\lambda \approx 9300$ Å, which we interpreted as the Lyman-α decrement (produced by intervening Hydrogen absorption), and by an emission line at wavelength $\lambda \approx 9334$, which we interpreted as Lyman-α. But because of the low signal-to-noise ratios of the identified spectral features, the redshift identification of galaxy A was not indisputable.

It is extremely difficult to obtain a confirming spectrum even with a 10 m class telescope on the ground because, at near-infrared wavelengths, background sky light is the dominant source of noise and confusing sky emission lines make identifications of spectral line features ambiguous. To strengthen the identifications of the faint galaxies observed in the STIS field, we acquired deep optical B, V, and R images of the STIS field with the WIYN telescope at the Kitt Peak National Observatory using the Mini Mosaic camera. The primary objective was to obtain sensitive photometry over a wide passband in order to provide strong constraints in the spectral energy distributions of these galaxies. In particular, a complete absence of flux at optical wavelengths shortward of the redshifted Lyman-α emission line due to intervening Hydrogen absorption would unambiguously confirm the previous redshift identification of galaxy A. The observations were carried out in a series of exposures of between 900 and $1,200$ s each in 2000 January. The total exposure times of the B, V, and R images were 2.3, 2.0, and 3.5 h, which reached 5 σ point source limiting AB magnitudes of ≈ 26.3, 26.0, and 26.7, respectively. The individual exposures were reduced using standard pipeline techniques and were registered to a common origin and filtered for cosmic rays.

To measure the energy fluxes of galaxies in the STIS field, we adopted a quasi-optimal photometry technique that fits model spatial profiles of detected objects to the individual ground-based images[2]. The model spatial profiles were obtained by convolving smooth models of the intrinsic profiles of detected objects (determined based on the direct image previously obtained with STIS using a non-negative least-squares image reconstruction method[3]) with appropriate point spread functions of individual images (approximated using a Gaussian profile). The new technique provides higher signal-to-noise ratio and more accurate flux uncertainty measurements than standard techniques, because it properly accounts for the variation of the point spread functions of individual frames (the full width at half maximum of which was measured to vary between 0.5 and 1.0 arcsec) and because it accounts for uncertainty correlations between nearby, overlapping neighbors.

We present the new ground-based B, V, and R images of galaxy A in Figure 1 together with the direct image obtained in the STIS clear filter. Contrary to expectations based on the previous analysis, galaxy A exhibits moderate detections of flux in all three ground-based images. Specifically, we estimate that galaxy A has B, V, and R magnitudes of $AB(B) = 26.7 \pm 0.2$, $AB(V) = 26.8 \pm 0.4$, $AB(R) = 27.3 \pm 0.4$, respectively. For a galaxy at redshift $z = 6.68$, both the B and V filters cover a wavelength range below the redshifted Lyman-α emission line. Therefore, the presence of optical flux in the B and V images indicates that galaxy A is very unlikely to be at redshift $z = 6.68$. Nevertheless, it is puzzling that the ground-based photometry do not seem to agree with the previous STIS photometry. Specifically, we find that for a STIS clear magnitude of $AB(\mathrm{clear}) = 27.67 \pm 0.09$, galaxy A is at least a factor of two too bright in the B and V filters when compared with known galaxy spectral energy distributions of any given redshift.

Figure 2 shows the spectral energy distribution of galaxy A established based on the broad-band photometry in the B, V, R (open circles), and STIS clear filters (open square) in comparison to the extracted one-dimensional STIS spectrum of galaxy A cast into 350 Å bins (open triangles). The spectral coverage of each filter is indicated by horizontal bars. It further shows that galaxy A has an extremely blue color, $AB(B) - AB(R) = -0.6 \pm 0.4$.

The only alternative for the new photometry to be in line with the previous measurement would be that a dominant portion of the flux observed in the STIS clear filter occurred within the spectral range covered by the B, V, and R filters (i.e. between 3500 and 9000 Å) and a negligible amount of flux at wavelengths below or beyond this range. The closest resemblance would be the spectral energy distribution of an F type star, but the apparent magnitude of this object would imply a distance of $\approx$ 450 kpc from the Sun, many times larger than the size of the Milky Way. We therefore conclude that this cannot be the case.

Because the STIS direct image (covering a wavelength range that spans from 2000 Å to 10000 Å) is a factor of $\approx$ 10 times more sensitive than the ground-based images and because STIS photometric calibration is accurate to within 5% (according to the STIS Instrument Handbook), it ought to provide a strong, reliable constraint in the integrated optical flux of galaxy A. To resolve the discrepancy between the ground-based and STIS photometry for galaxy A, we first examined the photometric calibration of the ground-based images. First, we measured photometry in the B, V, and R images for all the 1067 objects in the Hubble Deep Field (HDF) region presented by Fernández-Soto, Lanzetta, & Yahil[4]. Next, we converted the ground-based B, V, and R photometry to the space-based F450W and F606W photometry using the transformation presented in Holtzman et al.[5] Finally, we compared our photometry of these objects with the ones presented in Fernández-Soto, Lanzetta, & Yahil[4]. We found that these measurements completely agreed with each other. We therefore concluded that the photometric calibration of the ground-based images was consistent with the space-based photometry and that the discrepant photometry was due to some other factor. Because the two sets of observations were taken two years apart, the discrepant photometry could suggest that galaxy A is variable. In particular, the observed blue $V - R$ color of galaxy A agrees with that of the supernova 1995K identified at $z = 0.479$[6]. But we cannot provide further support to the hypothesis.

Regardless of the peculiarity of the spectral energy distribution of galaxy A, the conflicting results from two separate analyses also suggest that the previous analysis of the STIS observations might be in error. We therefore examined carefully the previous analysis, particularly the spectral extraction technique.

The primary arguments that were presented by Chen, Lanzetta, & Pascarelle[1] to support the confidence of the redshift identification were (1) consistent flux measurements from the direct image ($AB(\mathrm{clear}) = 27.67 \pm 0.09$) and the dispersed image ($AB(\mathrm{clear}) = 27.72 \pm 0.29$), (2) a robust detection of the emission line at $\lambda \approx 9334$, and (3) a statistically significant detection of the flux discontinuity at $\lambda \approx 9300$ Å that coincided with the emission line. We confirmed the detection of the emission line and the flux discontinuity using traditional spectral extraction techniques, but we were unable to confirm the amplitude of the flux discontinuity. The amplitude of the flux discontinuity could be overestimated in the previous analysis due to small systematic errors in the sky determination of the dispersed image, but we do not find evidence for that.

The results of our analysis show that galaxy A exhibits peculiar spectral properties that cannot be explained by either galaxies or stars. We cannot resolve the incompatible photometry of the new ground-based images and the previous STIS images. Therefore, we conclude that the redshift identification of galaxy A remains undetermined.

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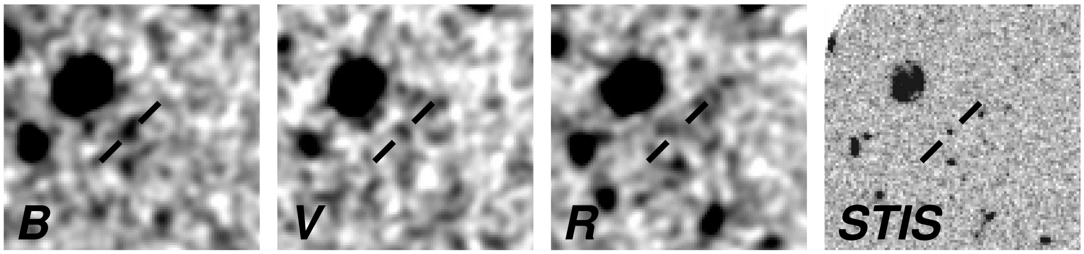
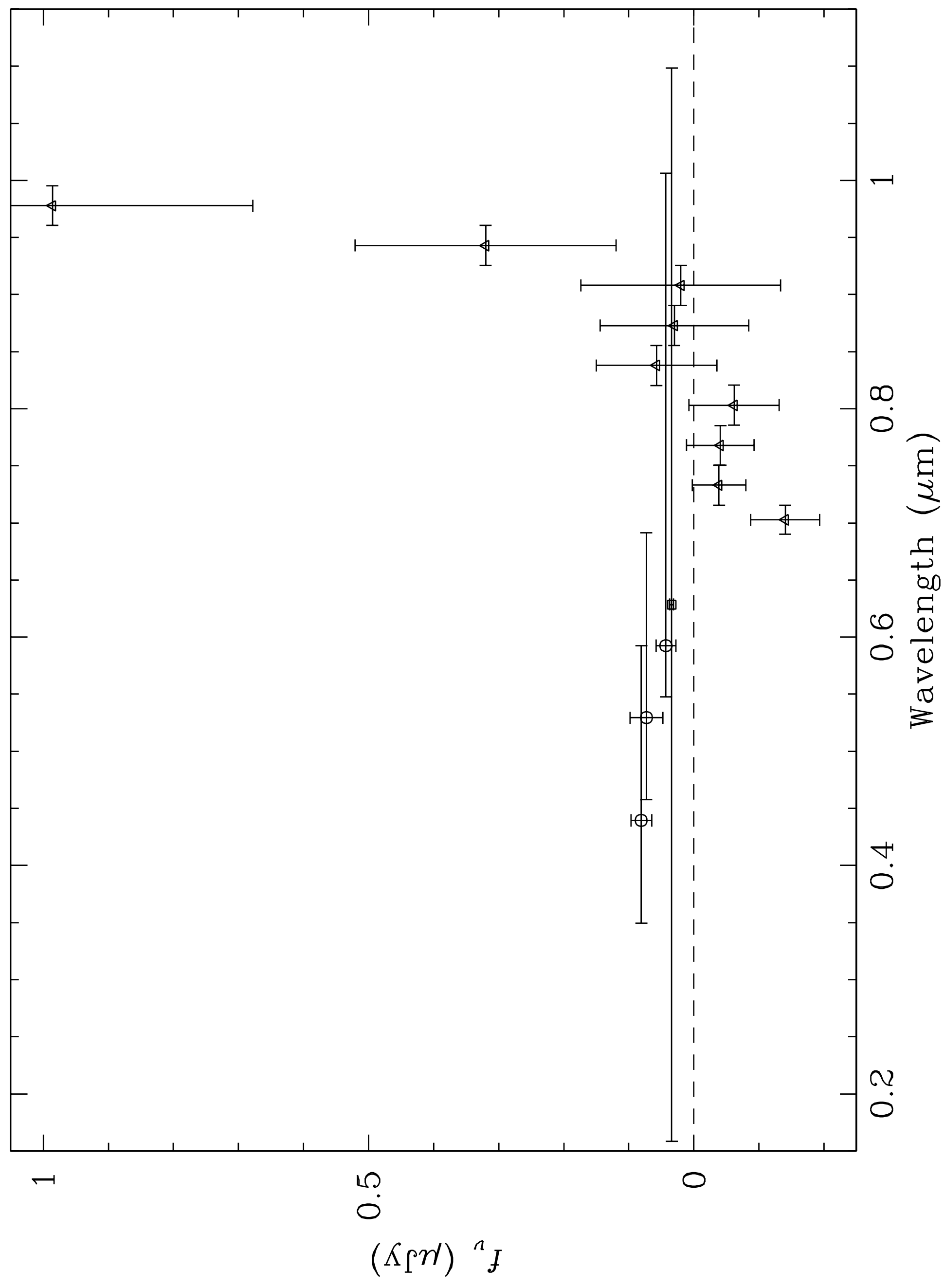
Fig. 1.— Portions of the ground-based B, V, and R images, smoothed by the size of the point spread functions, and the corresponding STIS image centered at galaxy A. Each panel is 14 arcsec on a side. North is to the left and East is down. The AB magnitudes of galaxy A are $AB(B) = 26.7\pm0.2$, $AB(V) = 26.8\pm0.4$, $AB(R) = 27.3\pm0.4$, and $AB(\mathrm{clear}) = 27.67\pm0.09$.

Fig. 2.— The observed spectral energy distribution of galaxy A. The open circles represent the broad-band photometry in the WIYN B, V, and R images. The open square represents the photometric measurement in the STIS clear filter. The open triangles represent the extracted one-dimensional STIS spectrum of galaxy A cast into 350 Å bins. The spectral coverage of each filter is indicated by horizontal bars.


B
V
R
STIS



Wavelength (μm)
0.2
0.4
0.6
0.8
1
f_ν (μJy)
1
0.5
0